Technical Challenges in Low-velocity SRF Development

ATLAS 25th Anniversary Celebration

October 22-23, 2010

Physics Division, Argonne National Laboratory

Building 203, Auditorium

Speaker: Mike Kelly

ATLAS Energy Upgrade: Commissioned June 2009
14.5 MV in 5 meters using 7 SC Quarter-wave Cavities

Superconductivity

Leiden,
ca. 1910

- 1911 – superconductivity discovered by Kamerlingh Onnes in a sample of Hg at 4 Kelvin
- 1950's:
  - Ginsburg-Landau theory developed
  - 1957 – Bardeen, Cooper, and Schrieffer theory
- First applications such as SC magnets
- 1964 – SC resonators developed for accelerator applications at Stanford

Outline

I. Some superconductivity background

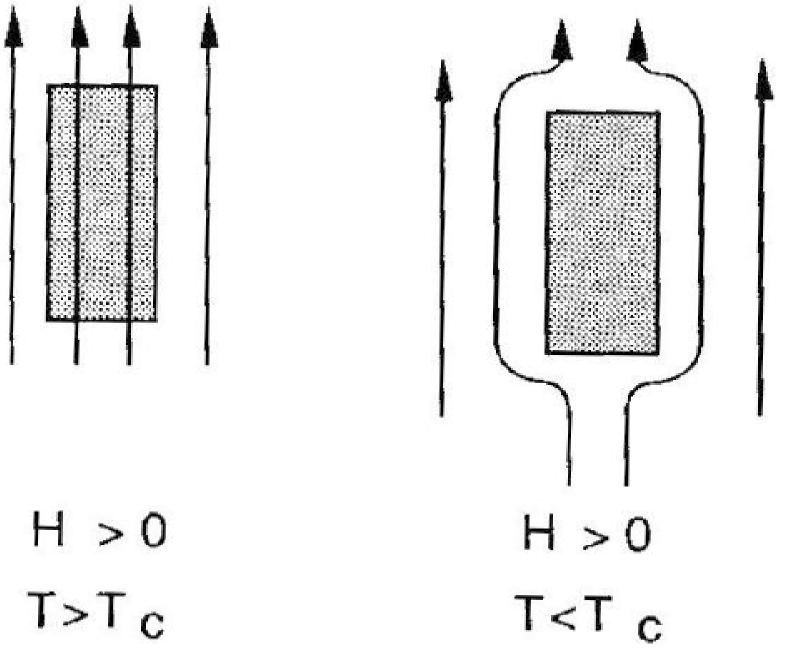
II. Progress in RF superconductivity

III. Outlook for the field

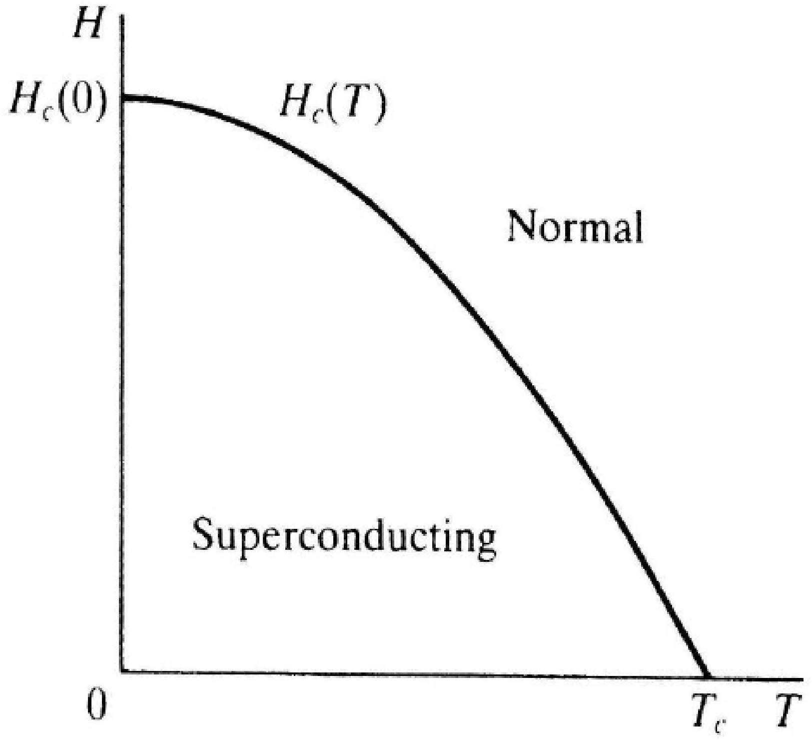
Materials from:

- Ken Shepard, Joel Fuerst

I. Meissner Effect and the Superconducting Phase Transition



The magnetic field penetrates into the superconductor a distance ***λ = 50nm for niobium***



Phase transition below T_c for $H_c(0)$

Maximum RF field is $H_{CRIT} \approx H_c$

I. Superconducting Surface Resistance
Skin Depth, Penetration Depth

Skin Depth and Surface Resistance at 1.0 GHz

T		Cu	Nb
293 K	Skin Depth	2.1 μm	6.1 μm
	Surface Resistance	8.2e-3 Ω/m^2	23e-3 Ω/m^2
~30 K	Skin Depth	0.2 μm	1.7 μm
	Surface Resistance	7.9e-4 Ω/m^2	6.3e-3 Ω/m^2
4.2 K	Penetration Depth	0.2 μm	0.05 μm
	Surface Resistance	7.9e-4 Ω/m^2	3.2e-7 Ω/m^2
2 K	Penetration Depth	0.2 μm	0.05 μm
	Surface Resistance	7.9e-4 Ω/m^2	6.5e-9 Ω/m^2

- SC Penetration depth does not vary appreciably with frequency
- SC surface resistance is lower by 3-5 orders of magnitude

I. Cryogenic Refrigeration Efficiency

	4.2 K	2 K
Carnot Efficiency	1.4%	0.6%
Mechanical Efficiency	0.3	0.2
Required Input Power	230 W per Watt	830 W per Watt

$$\eta_c = \frac{T}{300 - T}$$

- Given the efficiency of present cryogenic refrigerators, the net wall-plug power savings can be in the range of 30 – 1000

I. RF Surface: Surface Resistance, RF losses, Quality Factor

$$R_S = R_{BCS}(T, \omega) + R_{RES}\left[n\Omega\right]$$

Surface resistance modeled as T, ω-dependent term plus everything else

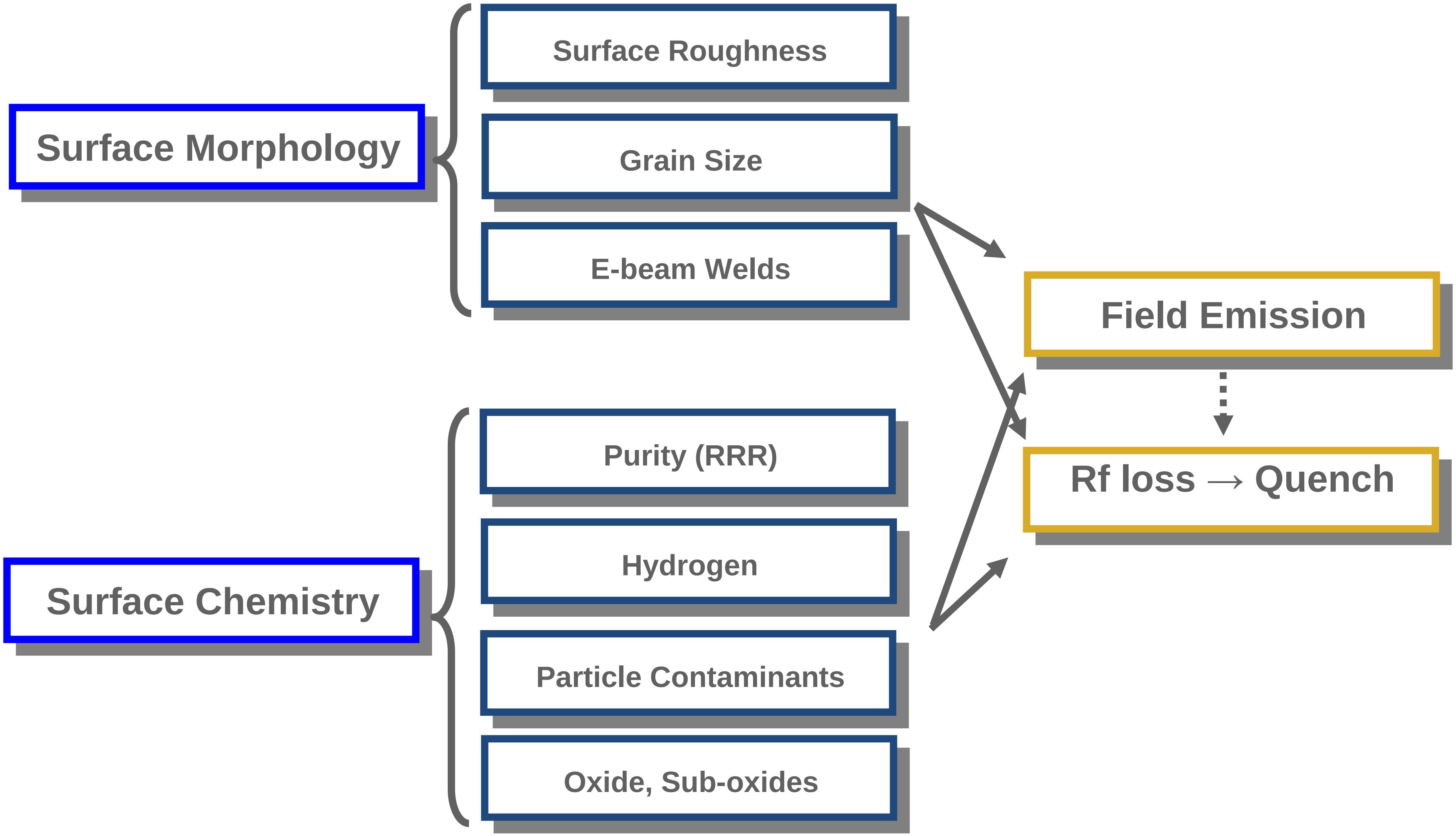
$$P_{IN} = \frac{1}{2}\oint R_S |H|^2 dA[Watts]$$

Power dissipated in the cavity walls is product of local R_s and the magnetic field squared over the cavity surface

$$Q_{Int} = \frac{U}{\Delta U} = \frac{U_o E_{ACC}^2}{P_{IN}} 2\pi f$$

Quality factor as for classical damped oscillator; stored energy divided by fractional energy loss per cycle

I. RF Surface: Properties in Bulk Niobium Cavities



Surface Morphology

- Surface Roughness
- Grain Size
- E-beam Welds

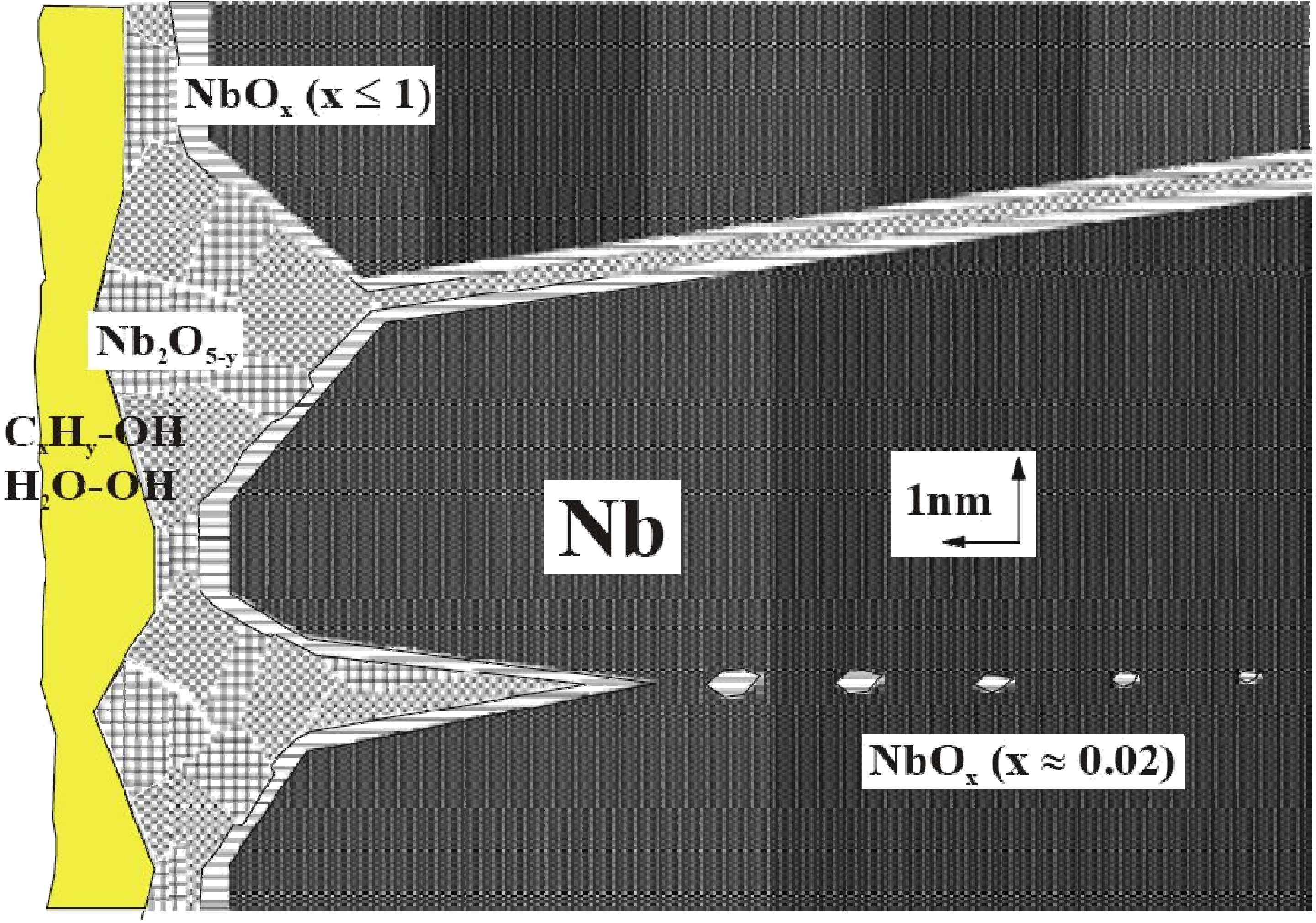
Surface Chemistry

- Purity (RRR)
- Hydrogen
- Particle Contaminants
- Oxide, Sub-oxides

Field Emission

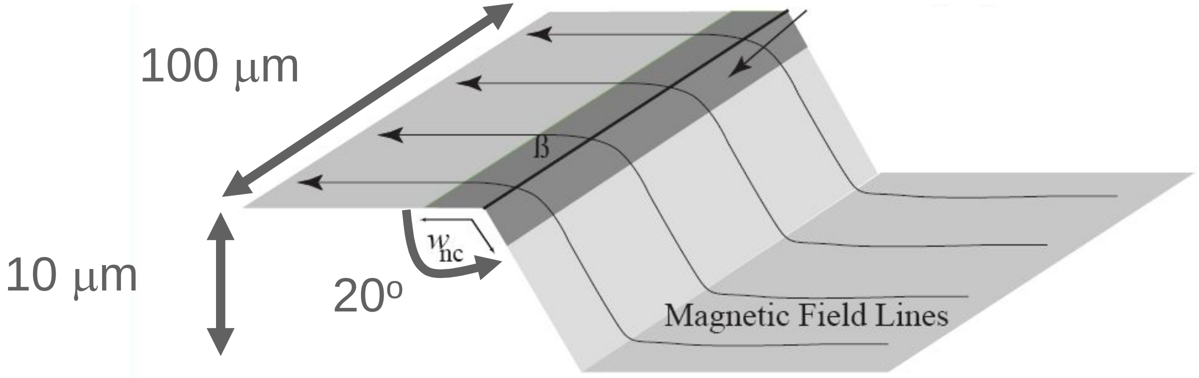
Rf loss → Quench

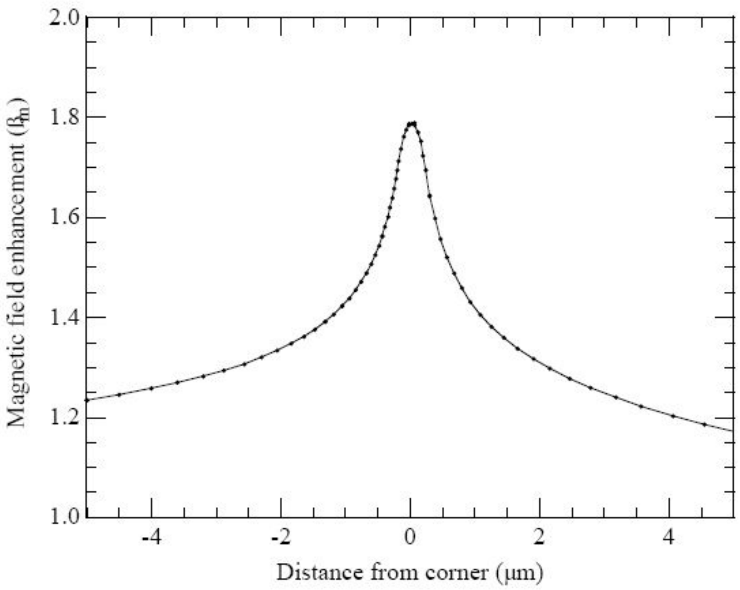
I. RF Surface: (Simplified) Niobium Surface

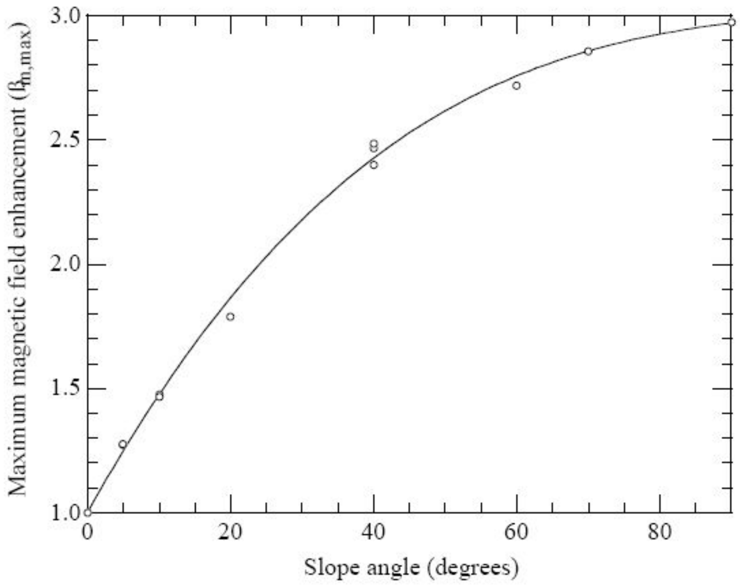


- Water, hydrocarbons adsorbed to the surface
- Several nm of Nb_2O_5 reforms rapidly even for low partial pressures of O_2
- Metallic NbO_x clusters

I. RF Surface: Surface Roughness

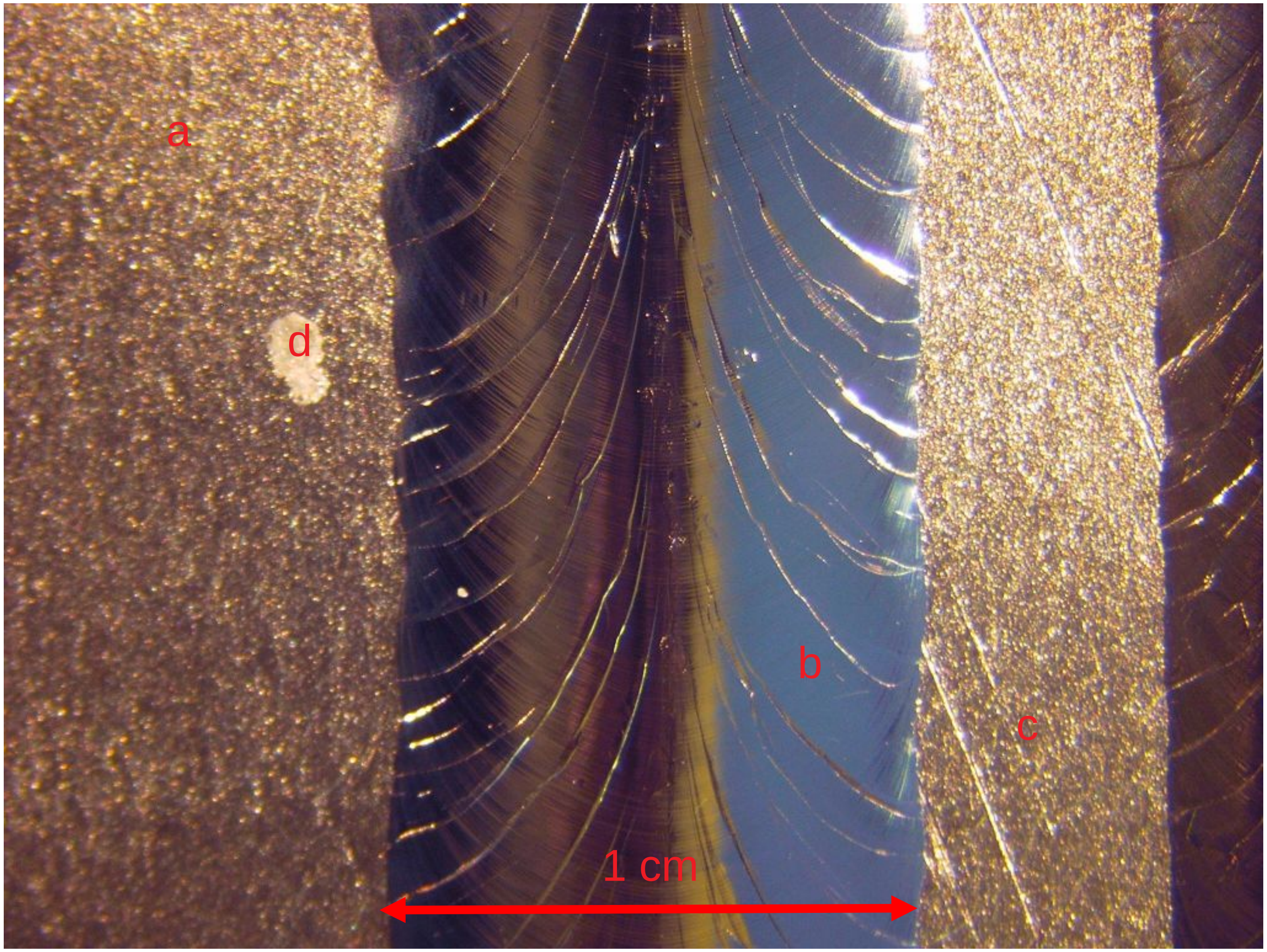






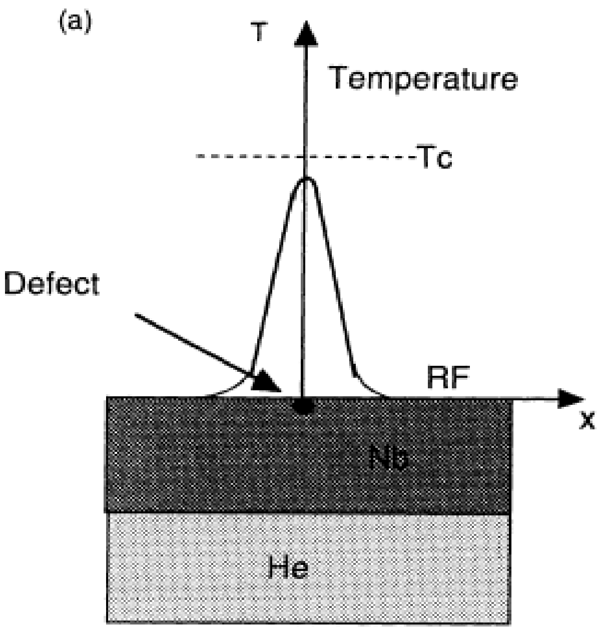
- Surface magnetic fields are enhanced when current runs along a (grain boundary) step
- Thermally stable regions of enhanced losses lead to a lowering of observed Q
- Low surface roughness likely to be key to achieving very high Q

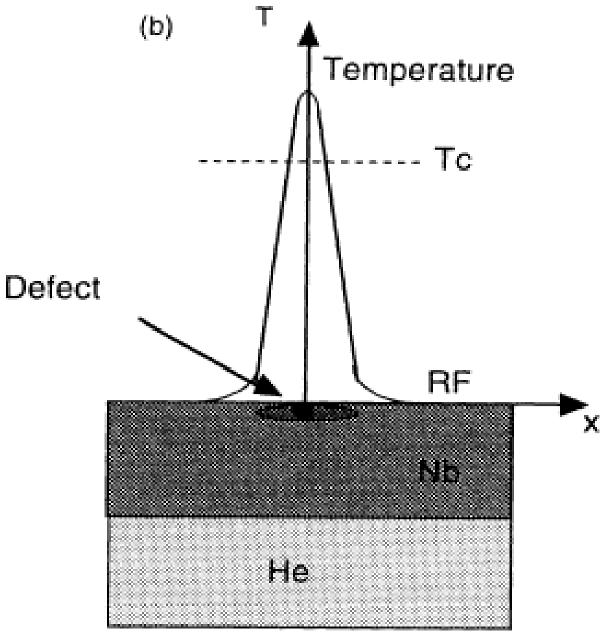
I. RF Surface: Grain Size and E-beam Welds

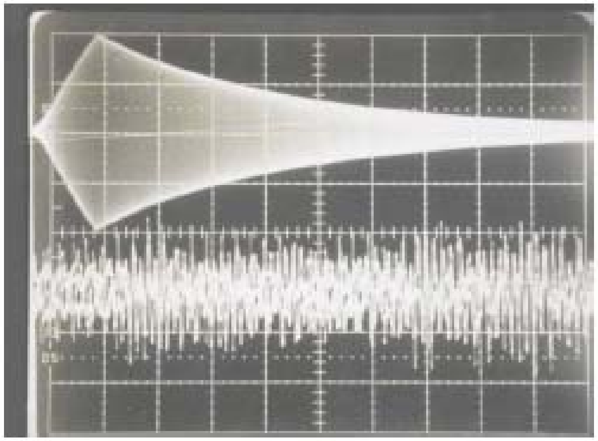


- Shown is a (typical) electron beam weld through 3 mm niobium sheet
- Surface is before final chemistry
- Visible features: Fine grains[a] (50 μm rms), large grain[b], scratches[c], defect[d]

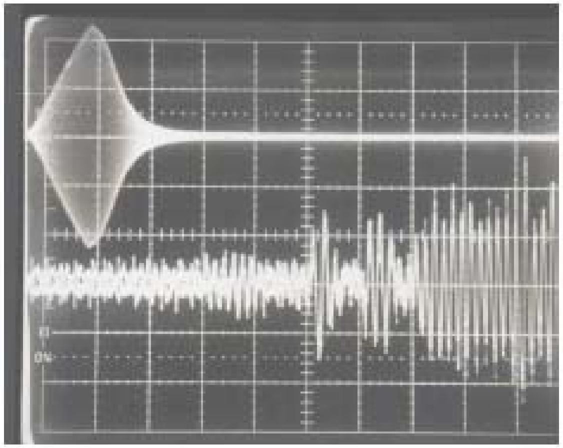
I. Thermal-Magnetic Breakdown







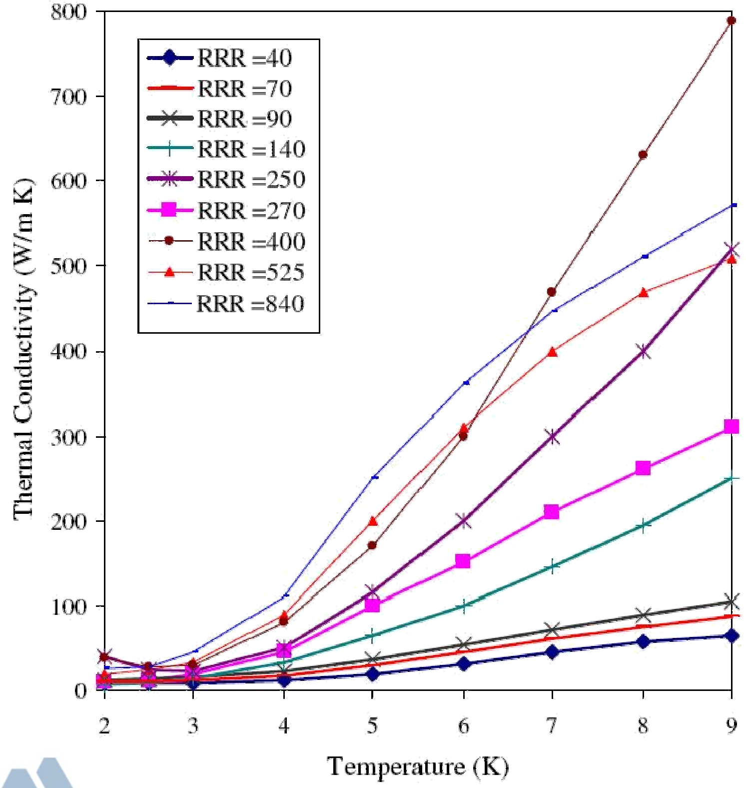
SC cavity being pulsed to a high field level. Horizontal scale is 5 msec/div



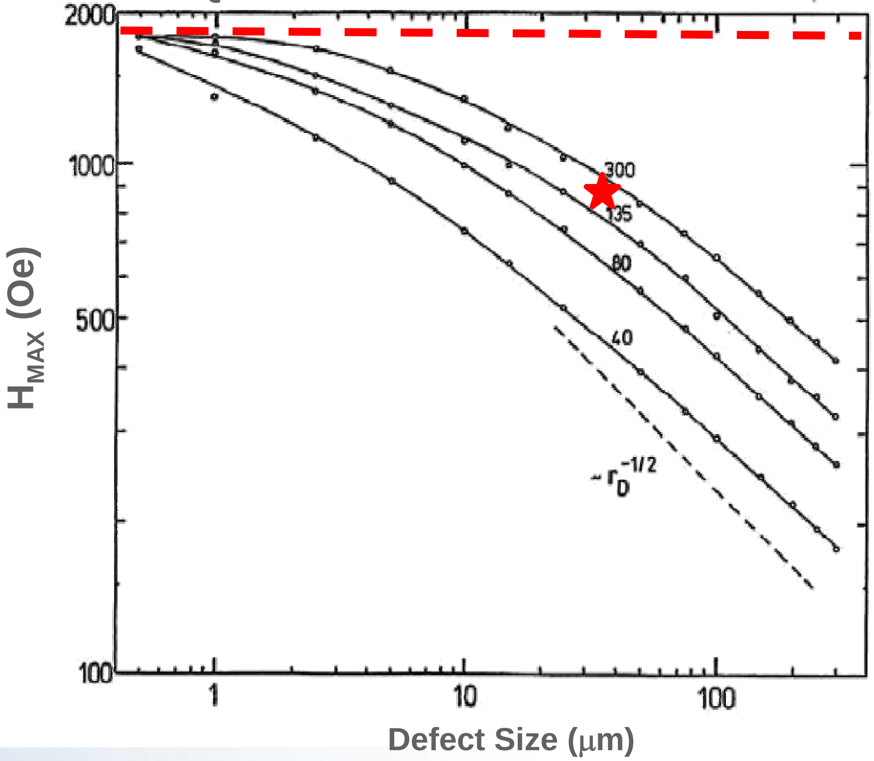
I. RF Surface: High Purity (RRR) as a method to increase the quench field

- Early SC cavities used RRR~40 (reactor grade)

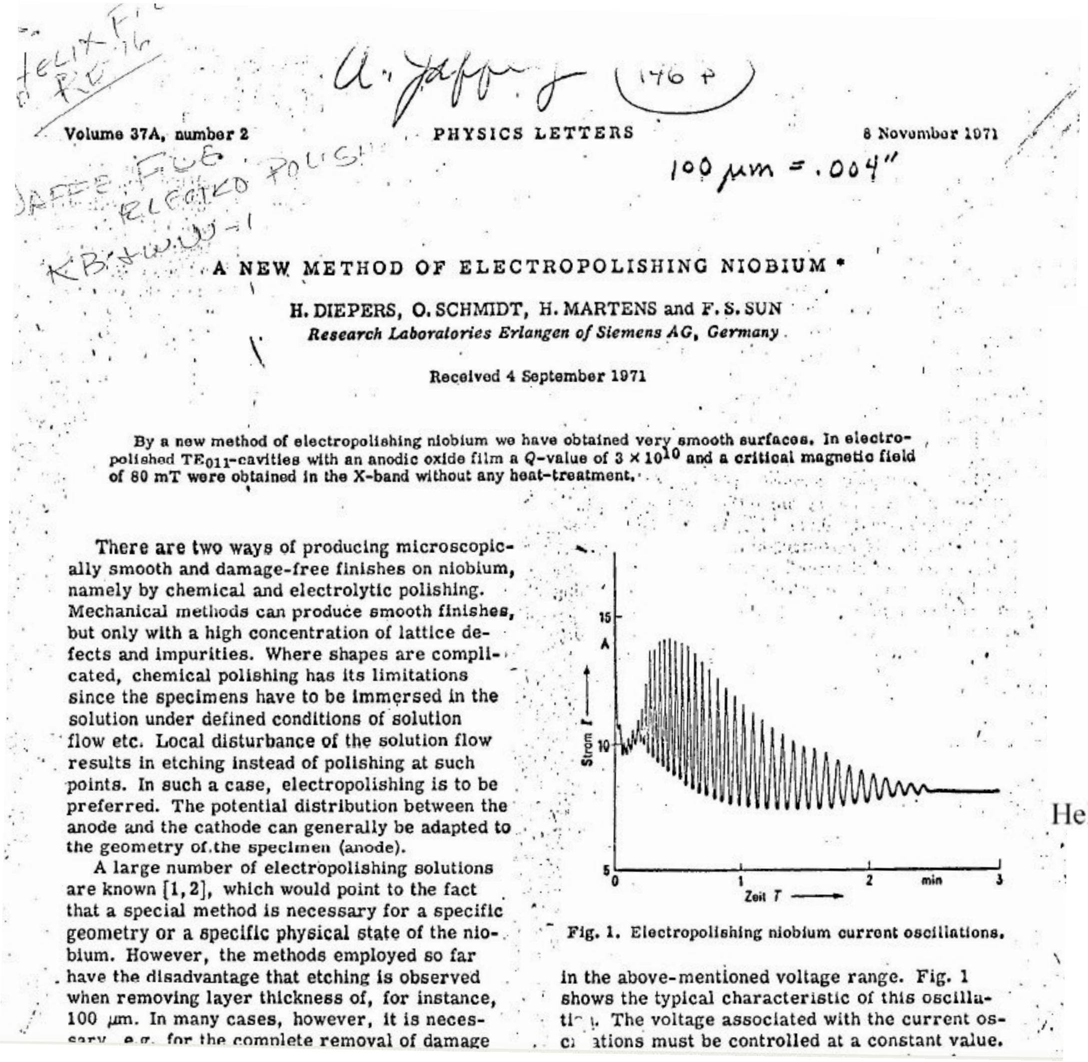
- Today SC cavities use RRR~250 or higher
- Carbon, Nitrogen, Oxygen – 10 ppm
- Titanium, Hafnium, Zirconium, Tungsten – 50 ppm
- Tantalum, Molybdenum – 500 ppm
- Hydrogen – 1 ppm



Quench Field vs Defect size



II. Four Decades of RF Superconductivity at ANL



JAFFE FILE ELECTRO POLISH

(146 P)

Volume 37A, number 2 PHYSICS LETTERS 8 November 1971

100 μm = .004"

A NEW METHOD OF ELECTROPOLISHING NIOBIUM *

H. DIEPERS, O. SCHMIDT, H. MARTENS and F. S. SUN
Research Laboratories Erlangen of Siemens AG, Germany

Received 4 September 1971

By a new method of electropolishing niobium we have obtained very smooth surfaces. In electropolished TE_{011}-cavities with an anodic oxide film a Q-value of 3×10^{10} and a critical magnetic field of 80 mT were obtained in the X-band without any heat-treatment.

There are two ways of producing microscopically smooth and damage-free finishes on niobium, namely by chemical and electrolytic polishing. Mechanical methods can produce smooth finishes, but only with a high concentration of lattice defects and impurities. Where shapes are complicated, chemical polishing has its limitations since the specimens have to be immersed in the solution under defined conditions of solution flow etc. Local disturbance of the solution flow results in etching instead of polishing at such points. In such a case, electropolishing is to be preferred. The potential distribution between the anode and the cathode can generally be adapted to the geometry of the specimen (anode).

A large number of electropolishing solutions are known [1,2], which would point to the fact that a special method is necessary for a specific geometry or a specific physical state of the niobium. However, the methods employed so far have the disadvantage that etching is observed when removing layer thickness of, for instance, 100 μm. In many cases, however, it is necessary, e.g. for the complete removal of damage

Fig. 1. Electropolishing niobium current oscillations.

in the above-mentioned voltage range. Fig. 1 shows the typical characteristic of this oscillation. The voltage associated with the current oscillations must be controlled at a constant value.

(EP collaboration between ANL and Karlsruhe)

Paul Markovich – ANL chemistry

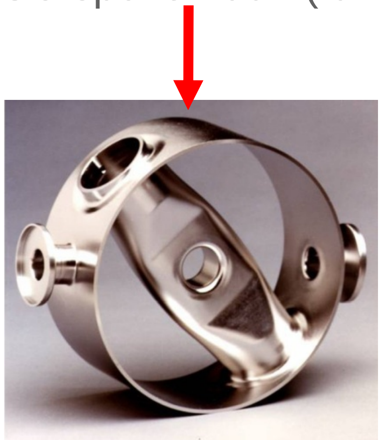
Helical Nb resonator developed at ANL for a heavy-ion linac.

II. SC Ion Linacs Around the World

II. Superconducting RF Structure for Electrons and Ions

97 MHz β=0.1 ANL

1st SC spoke 1991 (funded through SDI)

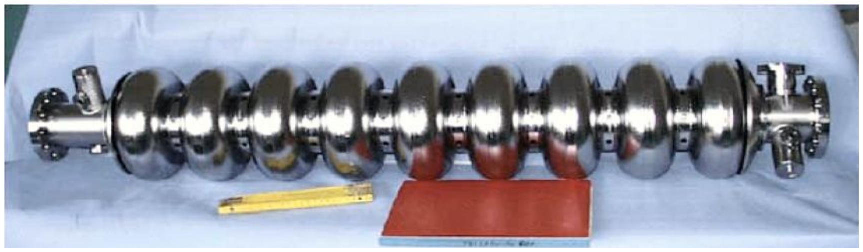


850 MHz β=0.28 ANL

High-Beta~1.0

805 MHz β=0.61 JLAB/SNS

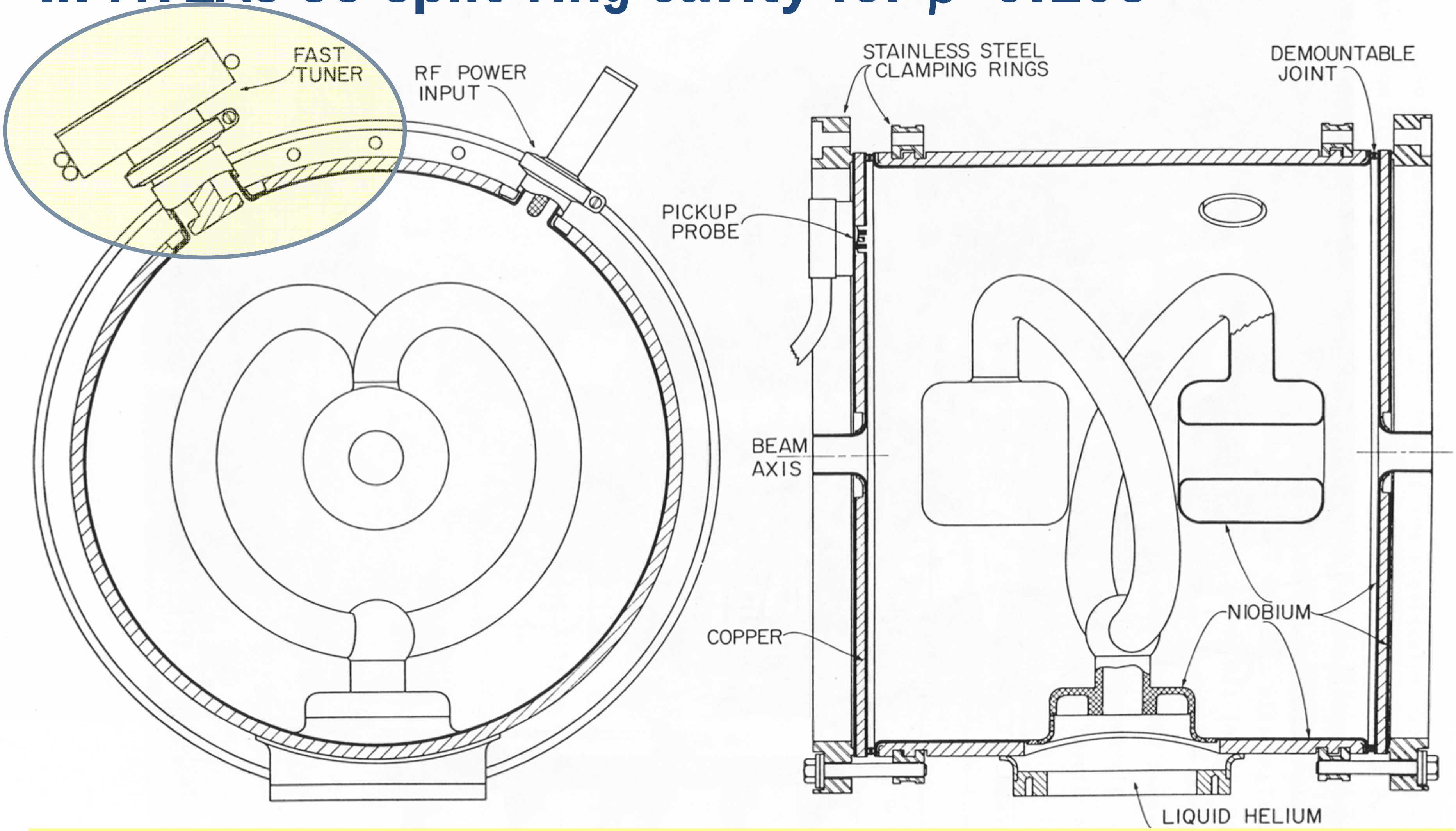
345 MHz β=0.63 ANL



1.3 GHz β=1 DESY

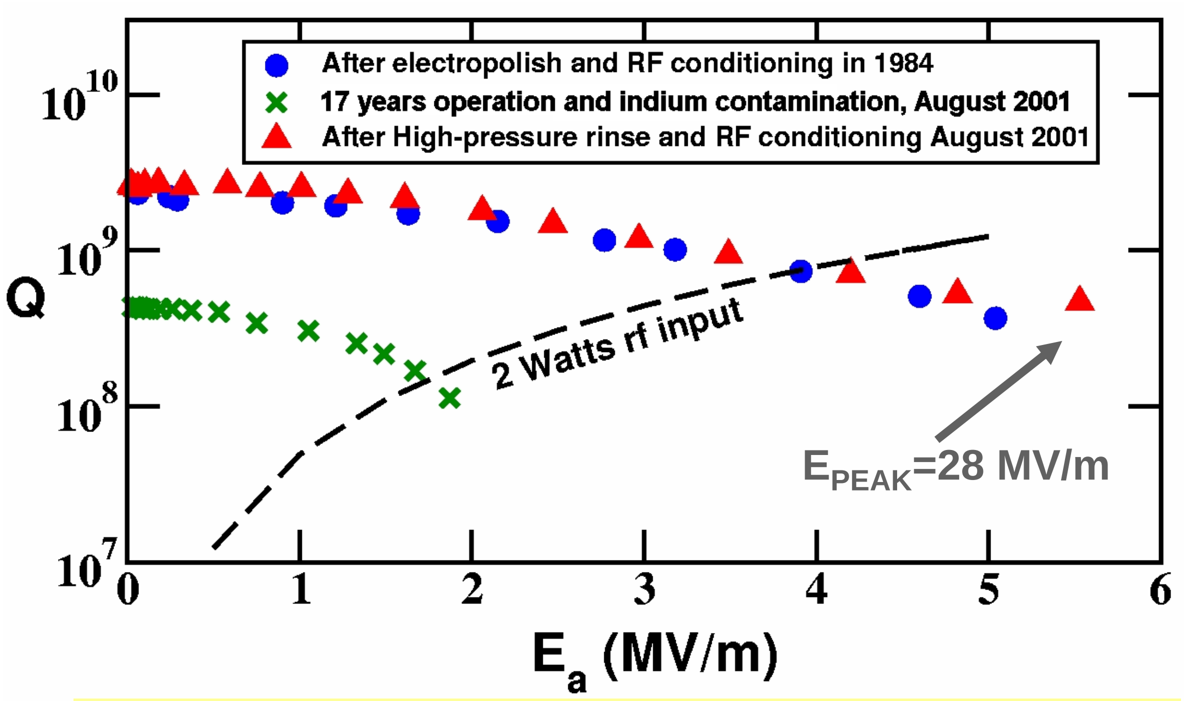
- Recent convergence of interest in SRF community; similar techniques now required for all cavities
- Bulk niobium remains the material of choice for today's high-performance SC cavities

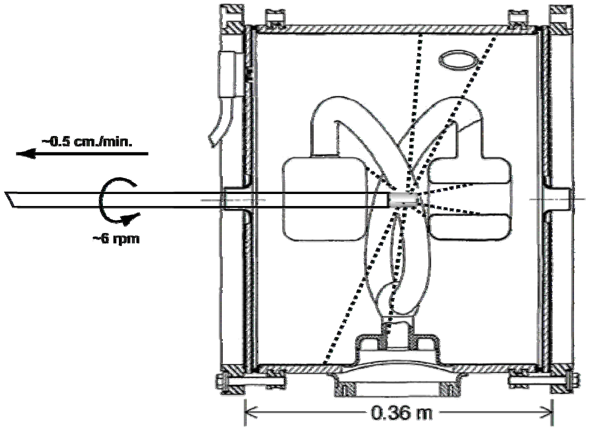
II. ATLAS SC Split-ring cavity for β=0.105



- Many important devlopments…development of the VCX fast tuner at ANL key to phase stabilizing an array of independently operated high-Q devices

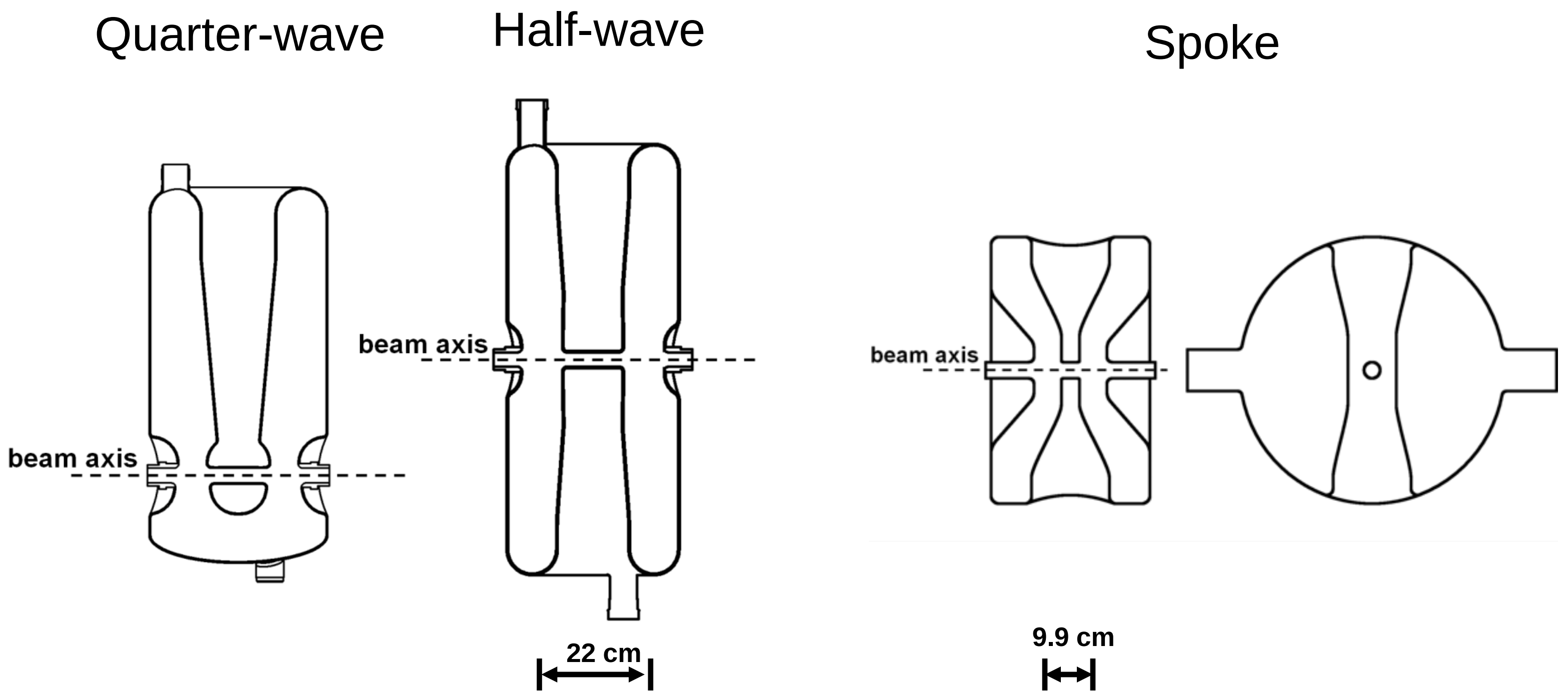
II. ATLAS SC Split-ring cavity





- Robust nature of SRF technology
- HPR after 17 years operations
  - The highest Q (>6x10^9 at 2 K)
  - CW accelerating fields (6.8 MV/m at 2 K, E_{PEAK}=34 MV/m)
  - Surface resistance (R_{RES}=2.7 nΩ)

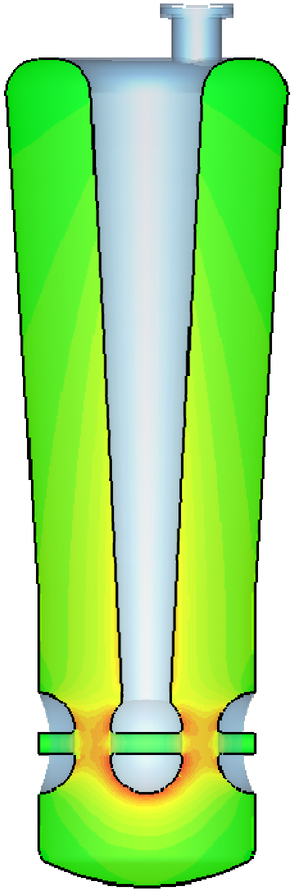
II. Modern low-beta TEM, a.k.a "drift-tube", cavities



- Operated in lowest TEM-like mode (higher order modes typically unimportant)
- $\lambda/4$ or $\lambda/2$ structures
- Physical dimensions $0.1<\ell<1$ meter
- Frequencies 50-800 MHz
- 4 Kelvin operation (Future 2 K @ f~325 MHz and above?)

II. Advanced Electromagnetic Design For a Quarter-wave Cavity (Intensity Upgrade QWR)

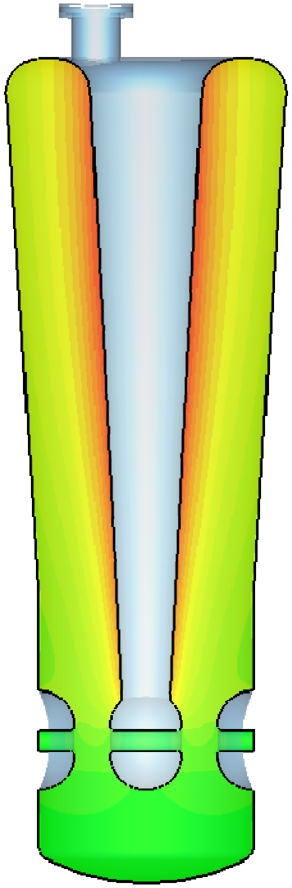
Quarter-wave cavity – half section view w/ volume fields



Electric Field

$E_p/E_{acc}=3.25$

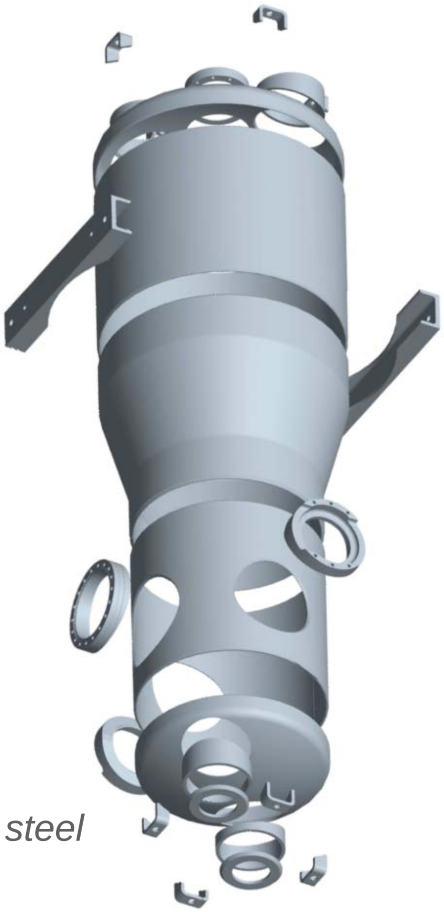
$L_{eff}=20$ cm



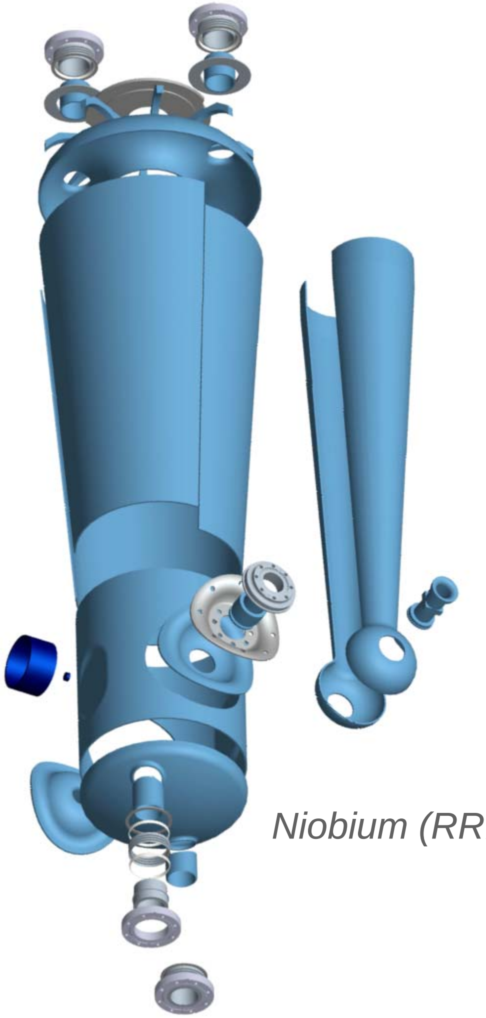
Magnetic Field

$$\frac{B_p}{E_{acc}} = 4.8 \frac{\text{mT}}{\text{MV/m}}$$

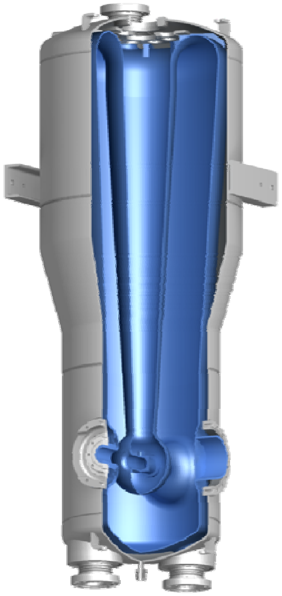
II. Mechanical Design for ANL Quarter-wave Cavity



Stainless steel



Niobium (RRR250)



Complete Assembly

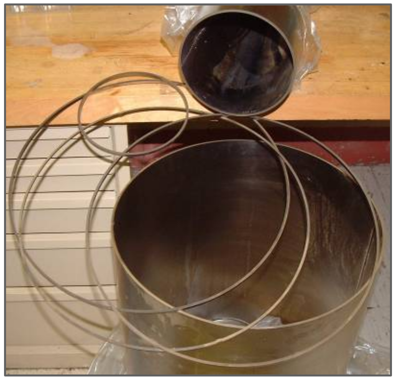
- Niobium is hydroformed or deep drawn all with blended transitions
- Stainless steel helium vessel assembled around the e-beam welded niobium cavity

II. ANL Has Worked to Develop US Vendors for SRF Cavity Fabrication

Hydroforming

- *AES*

- Niobium die hydroforming
- Conventional machining/wire EDM
- Electron beam welding
- Stainless steel helium jacket



Wire EDM/Machining

- *Numerical Precision*
- *Adron*

Electron beam welding

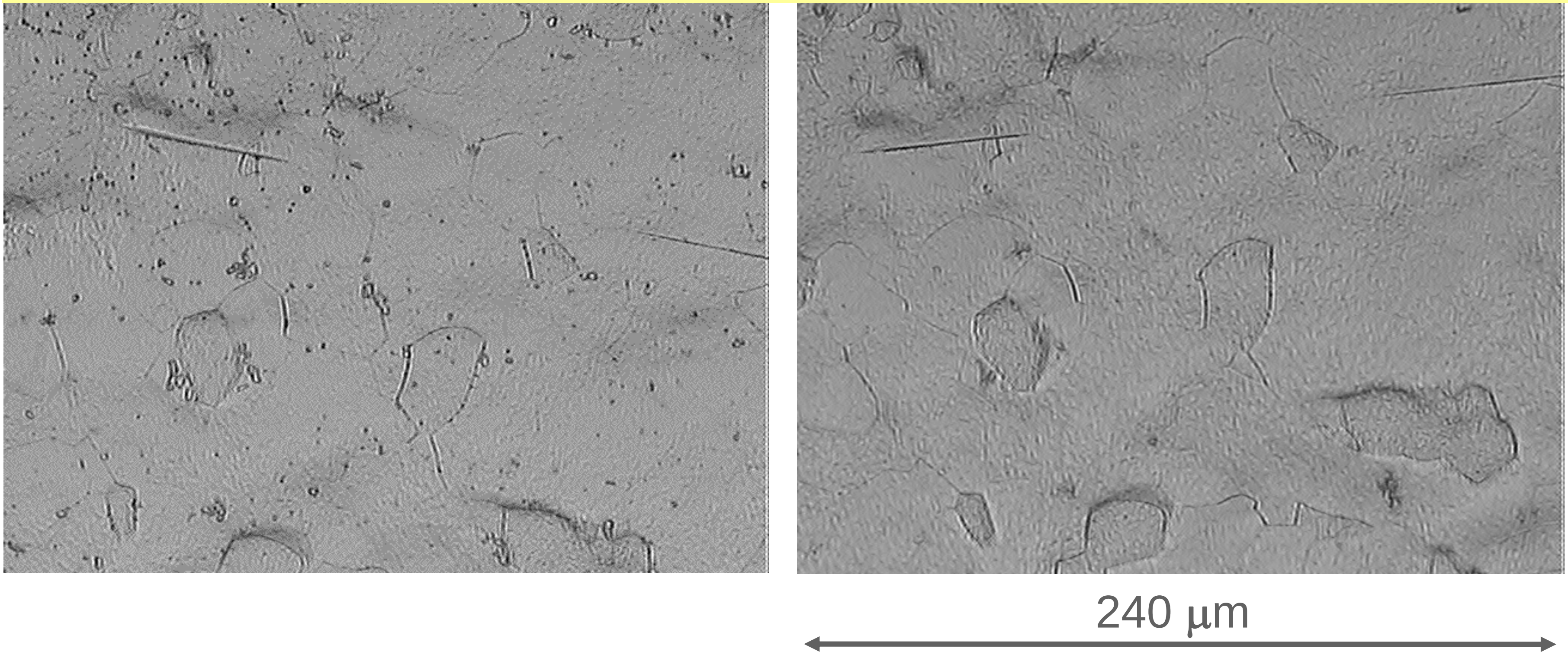
- *Sciaky*

Cavity housing/Cryogenic vessels

- *Meyer Tool*

II. Practical Considerations: HPR to Remove Particulates From an Electropolished Niobium Surface

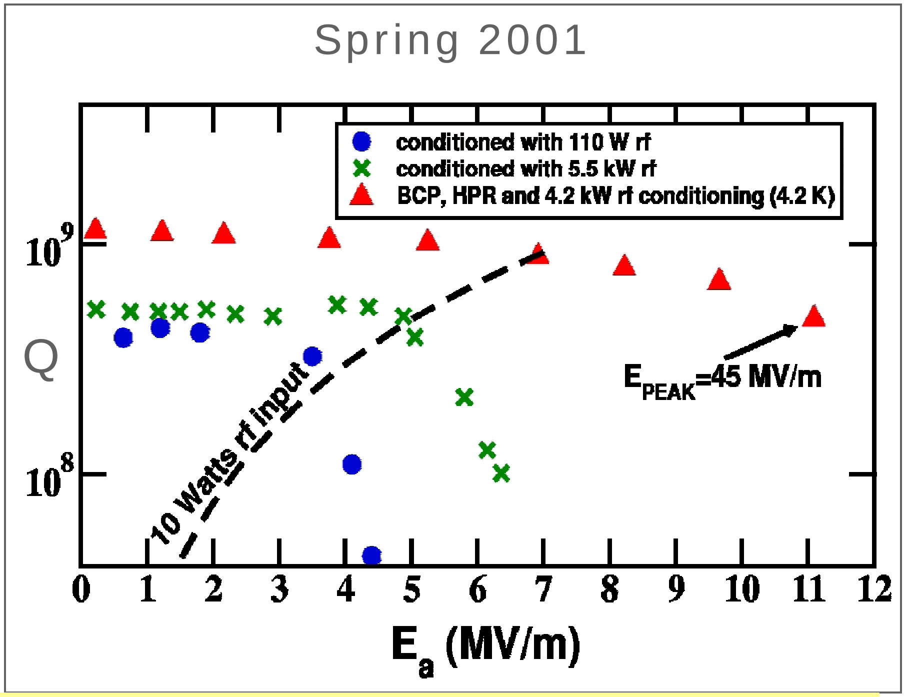
- Particulates are the most important cause of field emission



- Adhesion forces bind particulates to the cavity surface
- A high velocity water jet (150 m/s) effectively remove particulates
- Practical limit ~ 1 μm

-adhesion forces scale as particle diameter, mechanical force scales as particle area

II. First systematic use clean room high-pressure rinsing with a low-β SRF cavity 10 years ago

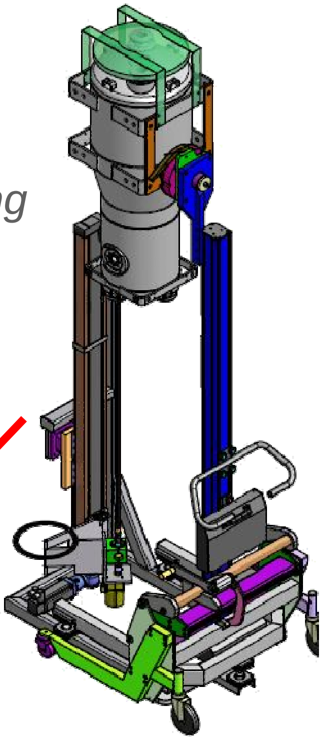


Dramatic performance increase from HPR consistent and repeatable if cavity kept clean

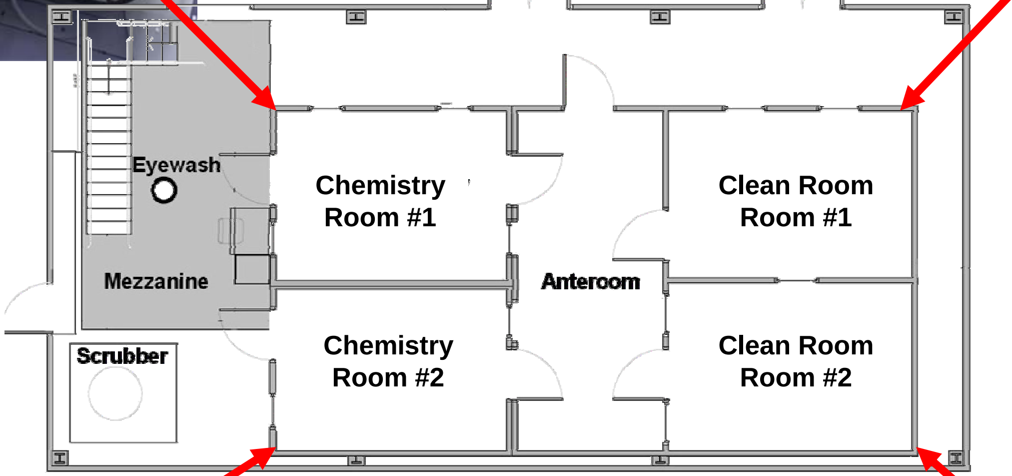
II. Superconducting Cavity Processing Facility at ANL

ILC/Project X
Electropolishing

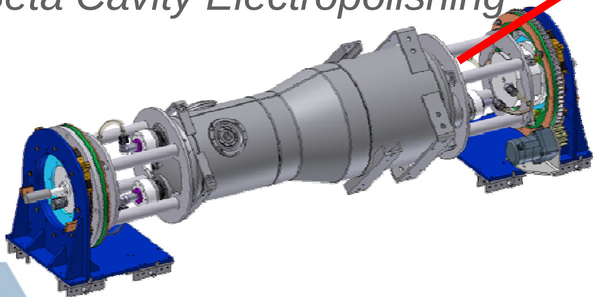
Low Beta Cavity Cleaning



Building 208 B-101 high-bay



Low Beta Cavity Electropolishing



ILC/Project X
Cleaning

II. Complete low-β superconducting cavity string with clean cavity vacuum

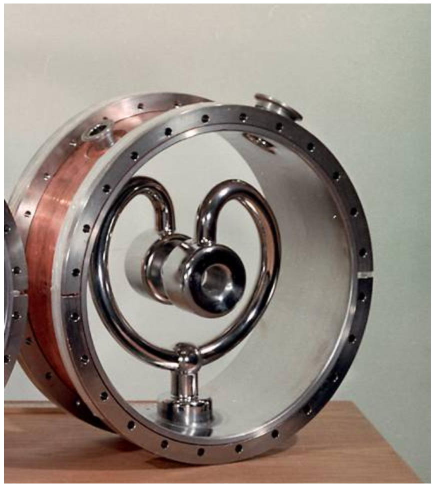
- A cryomodule containing 7 **β=0.15 quarter-wave cavities** has been added to the ATLAS heavy ion linac, increasing beam energy by 30-40%

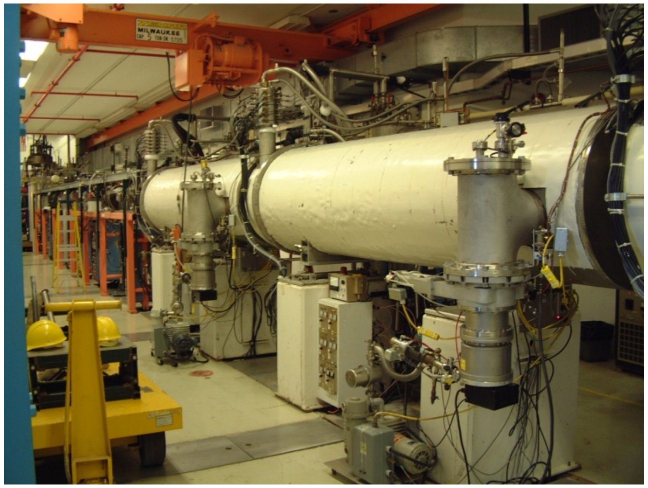
- Maximum voltages of **3.75 MV per cavity** have been achieved (E_{PEAK} = 48 MV/m, B_{PEAK} = 88 mT)

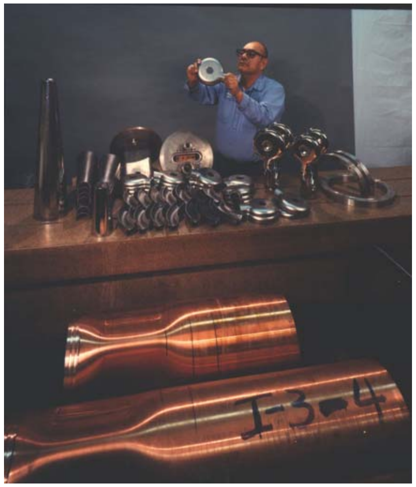
- Highest real gradient for operational cavities in this range of beta, with **14.5 MV accelerating potential in 4.6 m module length**

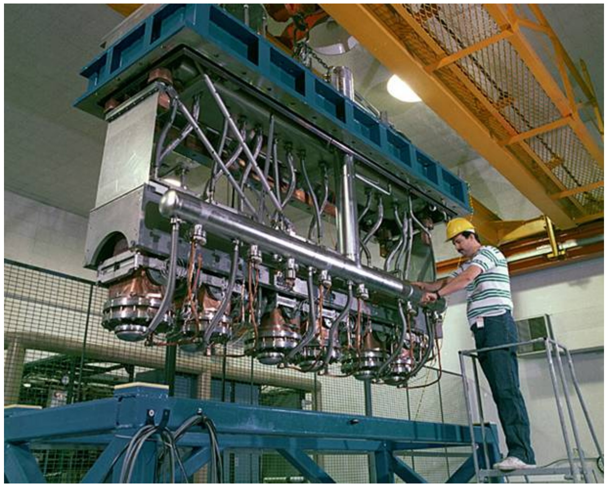
II. Evolution of ATLAS Cavities and Cryomodules

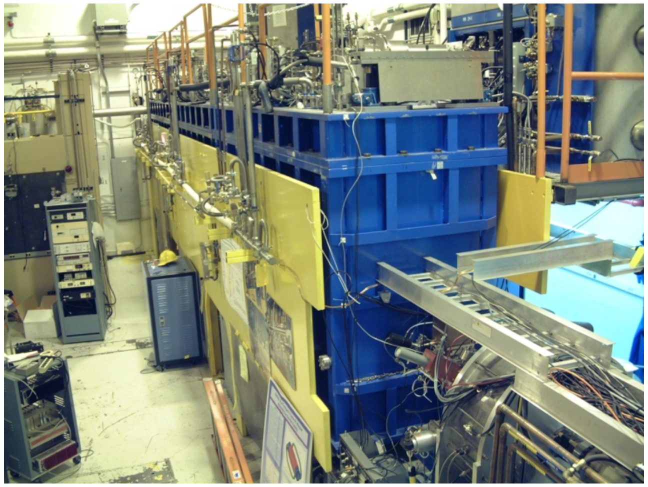
- Split-ring in cylindrical modules
- Top-loading box style cryomodules with low-velocity interdigital cavities



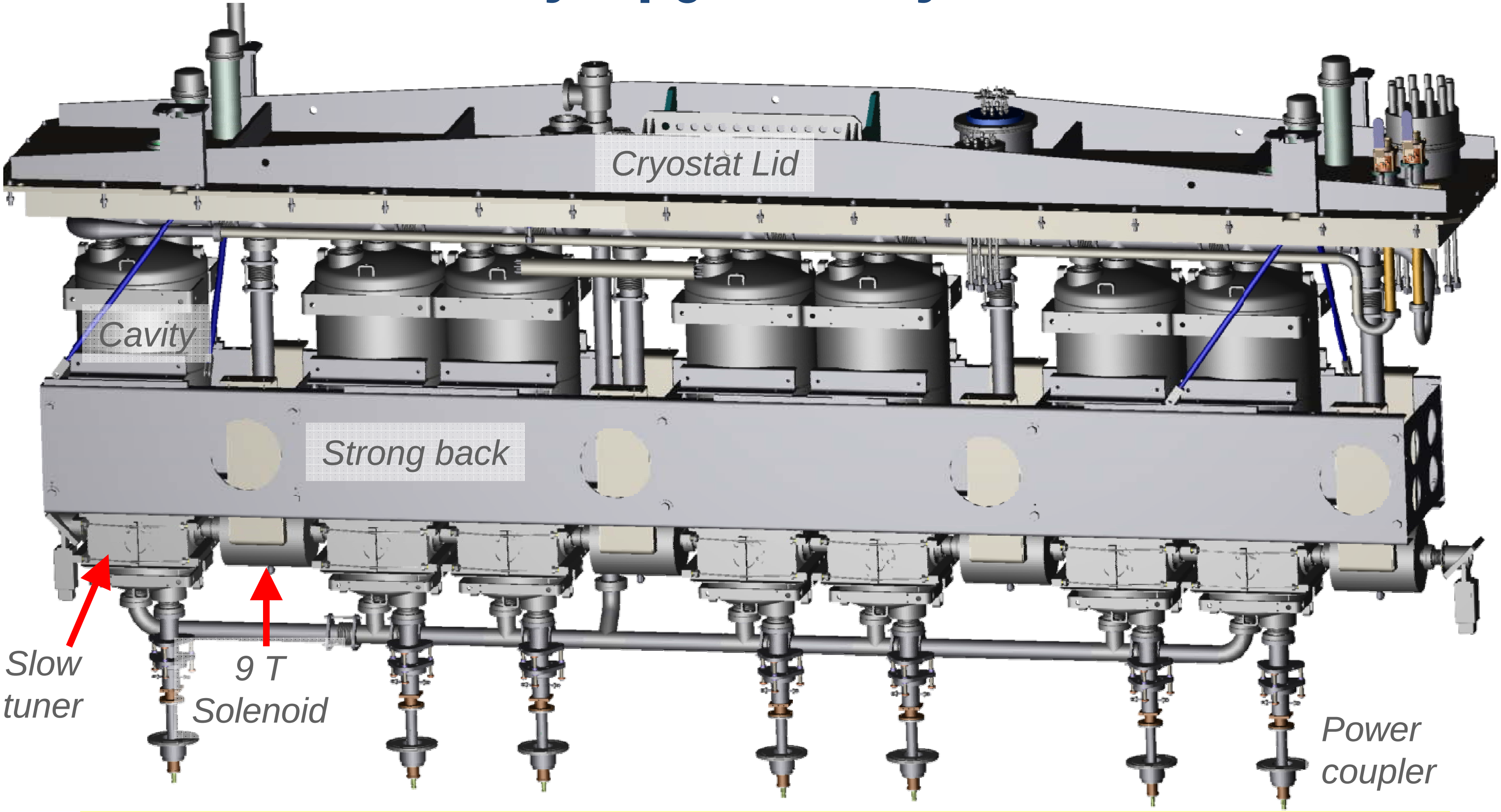








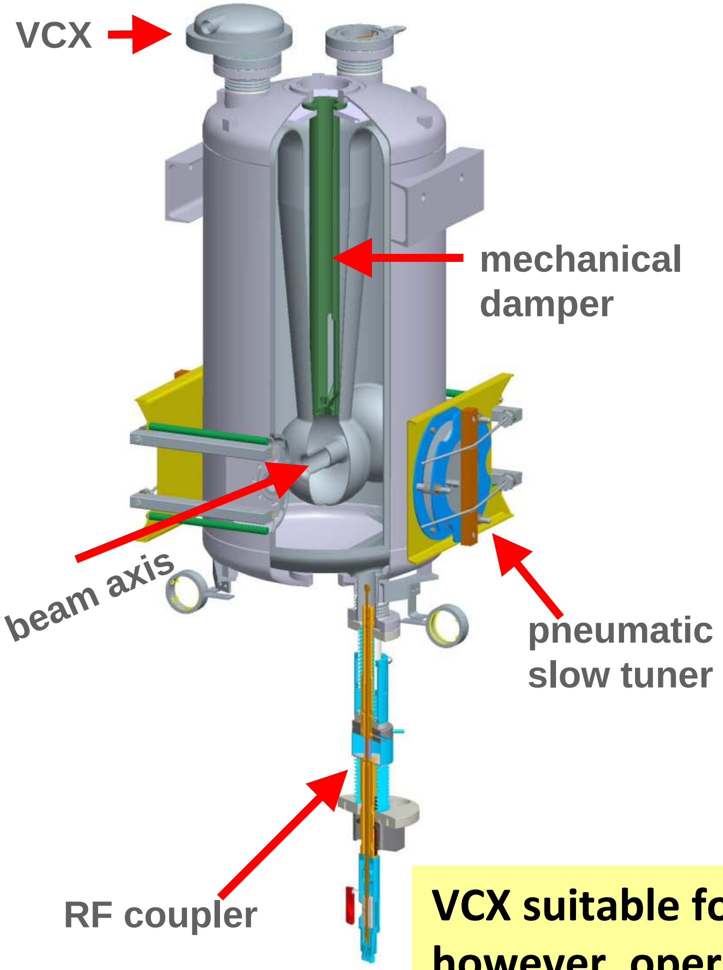
II. ATLAS Intensity Upgrade Cryomodule: 2012



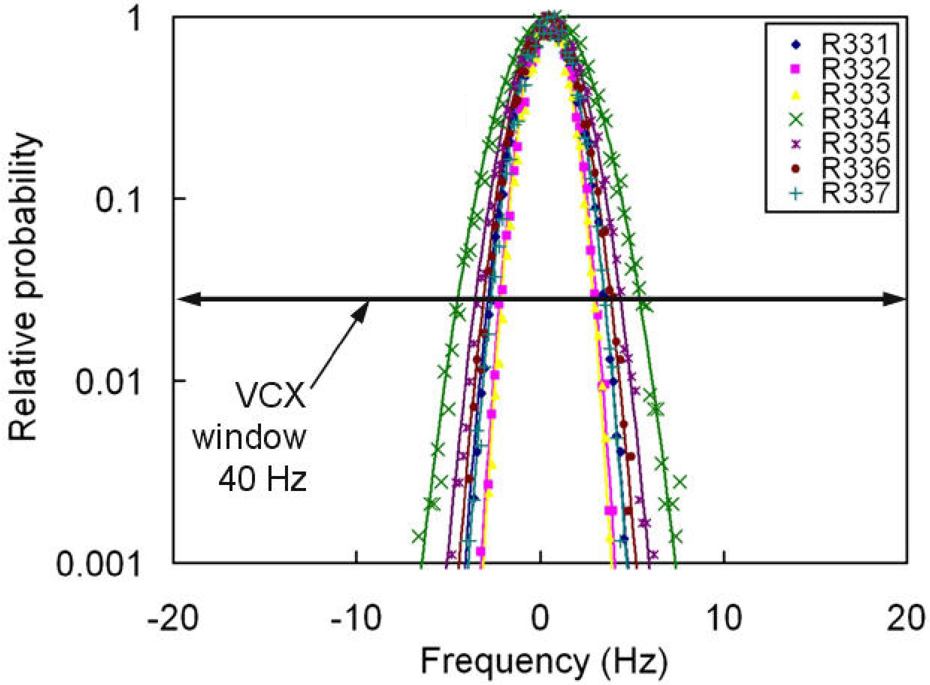
Many similar features previous module; exceptions are:

- New fast tuning system
- Based on a high power (4 kW) RF power coupler/mechanical (piezoelectric) fast tuner

II. Cavity Microphonics: Presently Operating Upgrade Cryomodule

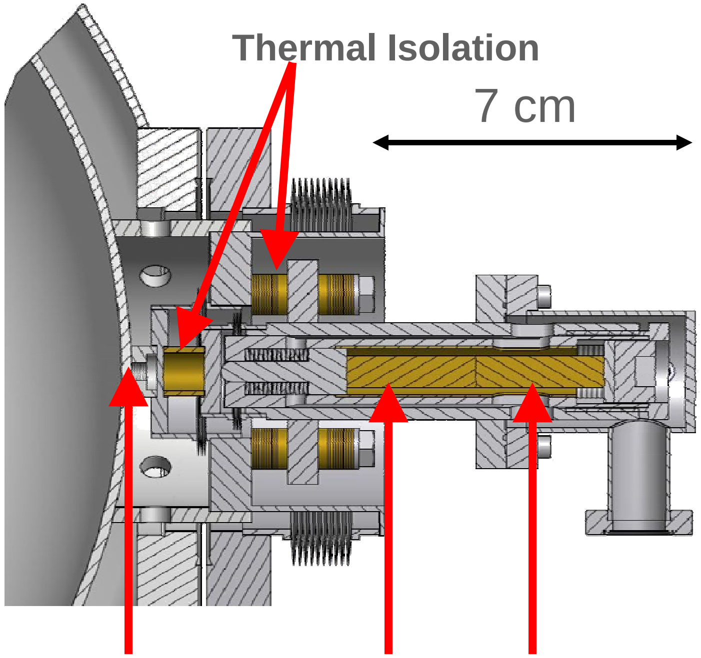


Measured data for cavity microphonics – all cavities at full operational gradient



VCX suitable for phase control window in presence of microphonics, however, operation limited to E_{ACC}~8 MV/m

II. A Small Piezoelectric-based mechanical fast tuner

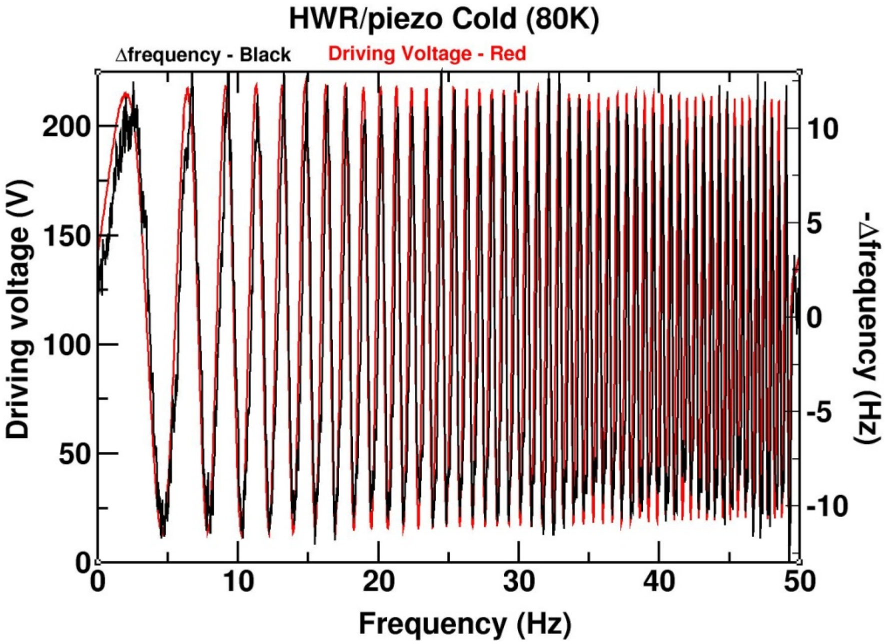


Thermal Isolation

7 cm

4 K Nb Cavity Wall

80 K Piezoelectric elements



Detailed cold testing on 170 MHz half-wave cavity completed

- Small heat leak
- Linear cavity frequency response up to ~90 Hz driving frequency
- *No additional microphonics introduced by tuner below 90 Hz*
- Long-term reliability testing to be done

III. Why Continue to Develop SRF

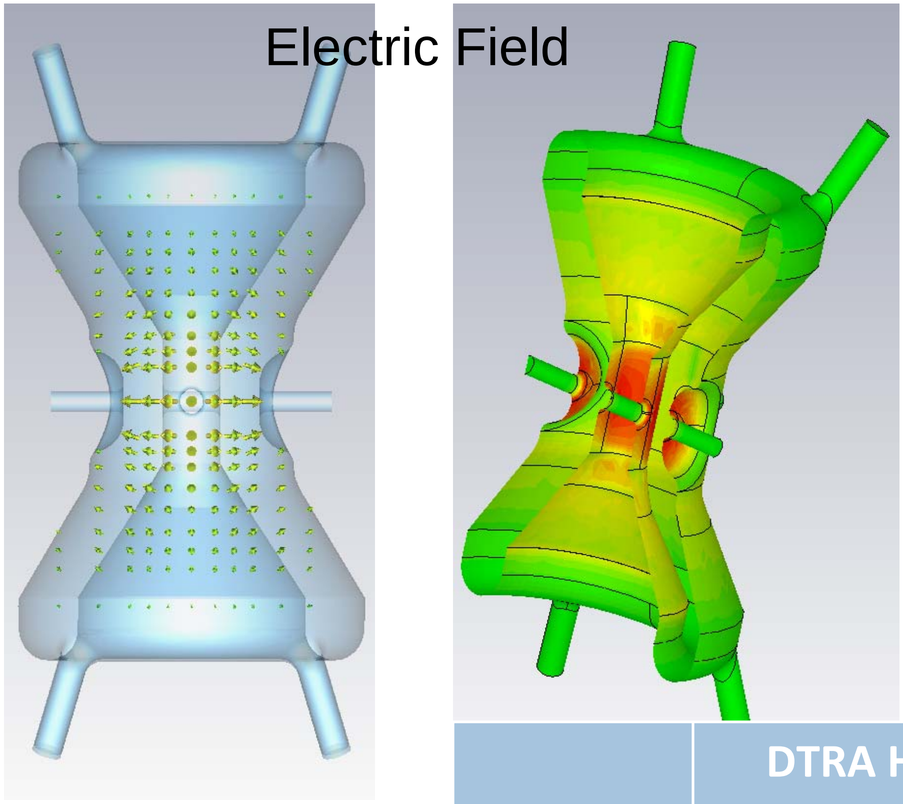
- Obvious benefits for ATLAS
  - Retire split-ring cryomodules
  - Higher beam energies
  - Higher beam intensities

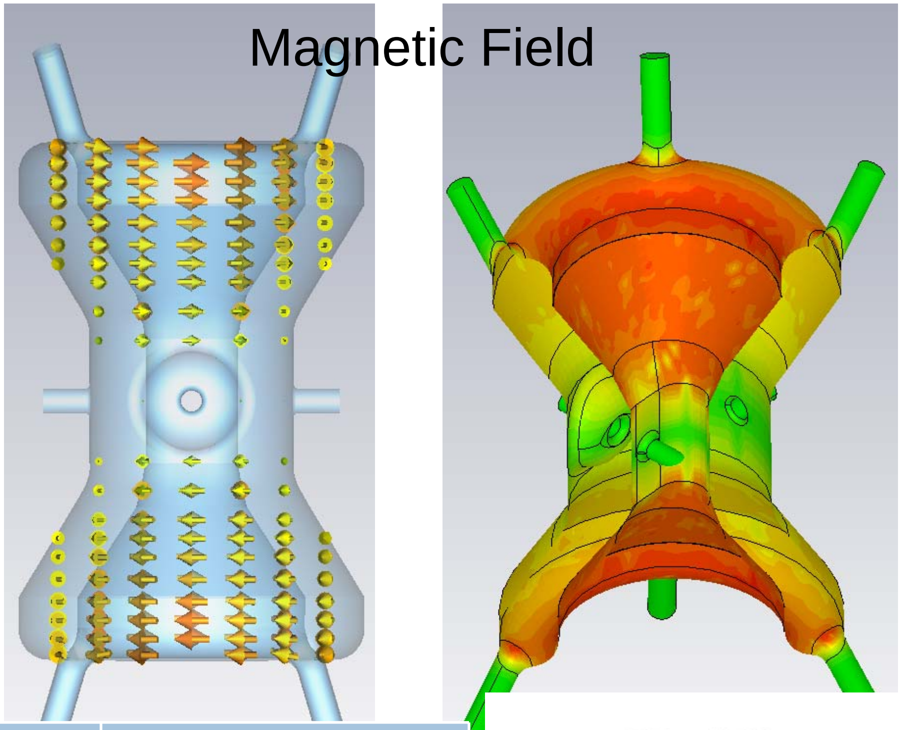
- New machines for basic science
  - Project X at Fermilab
  - SARAF in Israel
  - FRIB at MSU

- Real possibilities for high-gradient low-beta for applications
  - National security (non-destructive interrogation methods)
  - Nuclear medicine (accelerators as solution to Mo99 crisis)
  - Accelerator Driven Systems (accelerators for energy production/waste transmutation)

III. A New Highly Optimized Half-wave Cavity Funded by DTRA (Defense Threat Reduction Agency)

Goal: Compact (1 GeV) proton accelerator for detection of special nuclear materials


Electric Field


Magnetic Field

	DTRA HWR	ANL RIA/FRIB HWR
E_{peak}/E_{acc}	2.6	2.9
B_{peak}/E_{acc}	3.9 mT/(MV/m)	7.8 mT/(MV/m)

Final Comments

- Outstanding technical developments in the field of superconducting RF for over four decades and ATLAS technology has been an important part of this
- Superconducting RF for particle accelerators continues to be a dynamic, rapidly evolving field
- *ATLAS has really served as the home base for an SRF team that has contributed many of the important developments for SC ion accelerators. I think it should and will continue to do so*
- *Its been a pleasure to work many talented people in Physics Division*